UNITED STATES PATENT APPLICATION
FOR GRANT OF LETTERS PATENT

REZA SHAHIDI
NIRMAL VELAYUDHAN

INVENTOR(S)

Fast Forward Power Control During Soft Handoff

FAST FORWARD POWER CONTROL DURING SOFT HANDOFF

RELATED APPLICATIONS

This application claims priority from U.S. Provisional Application No. 60/272,999

filed March 2, 2001 entitled "Power Offset Reduction Algorithm During Soft Handoff For

5   Fast Forward Power Control."

BACKGROUND OF THE INVENTION

The present invention relates generally to methods of power control for wireless

communication systems and, more particularly, to methods of forward link power control

10   during soft handoff.

Numerous access schemes exist to allow multiple users to share a

communication medium. One such access scheme is known as Code Division Multiple

Access (CDMA). In CDMA systems, multiple users share the same carrier frequency

and may transmit simultaneously. Each user has its own pseudo-noise (PN) sequence,

15   which is approximately orthogonal to the PN sequences of other users. Transmissions

to or from individual users are imprinted with that user's PN sequence. The receiver

selects the desired signal, which combines with unwanted signal during transmission, by

correlating the received signal with the PN sequence of the desired signal. All other

undesired signals are spread by the PN sequence and appear as noise to the receiver.

20   Two standards for CDMA systems currently used in the United States are the IS-

95 standard and the cdma2000 standard, which are described in specifications

published by the Telecommunications Industry Association and Electronics Industry

Association (TIA/EIA). The IS-95 standard was developed primarily for voice services

and low rate data services. cdma2000 is a spread-spectrum radio interface that uses

25   CDMA technology to satisfy the needs of third generation wireless communication

systems. A significant benefit of cdma2000 is the ability to provide high-rate data

services, in addition to voice services, for web browsing and other high data rate

applications. In web browsing, the amount of traffic on the forward link is typically much

larger than amount of traffic on the reverse link. Therefore, it is particularly important to

increase spectrum efficiency, particularly on the forward link.

5   CDMA systems are inherently interference-limited systems. Since all mobile

stations operate at the same frequency, internal interference generated within the

system plays a critical role in determining system capacity and voice quality. Two

closely related techniques used in CDMA systems to reduce interference and thereby

increase system capacity are power control and soft handoffs.

10   Power control is used on the forward link in CDMA systems to control the power

of signals received at each mobile station. To maximize system capacity, the system

allocates power to individual mobile stations according to the interference levels at each

mobile station. The purpose of forward link power control is to ensure that each mobile

station receives signals on the forward link at a desired minimum signal to interference

15 ratio (SIR). The minimum SIR is chosen by the system operator to ensure a desired

quality of service. Thus, the base stations transmit with highest power to those mobile

stations with the highest interference levels, and with lesser power to mobile stations

with lower levels of interference. In CDMA systems, the system capacity is maximized if

the transmit power level of each base station is controlled so that its signals arrive at the

20 mobile station receiver with the minimum required SIR.

As the mobile station moves around within the network, the channel conditions

change continuously due to fast and slow fading, shadowing, number of users, external

interference, and other factors. Power control algorithms dynamically control the

transmitted power on the forward link to maintain the minimum SIR at the mobile station

25 under all conditions. Two forward link power control mechanisms are employed in

conventional CDMA systems: slow forward power control and fast forward power control.

In slow forward power control the mobile station keeps track of the number of error frames and if the number of error frames over the designated period exceeds a threshold, the mobile station sends a Power Measurement Report Message (PMRM) to the base station containing the total number of frames received in the period, the

5 number of error frames, and the frame error rate (FER). On receiving the PMRM, the base station adjusts its transmit power based on the reported frame error rate.

Fading sources in mobile radio systems require much faster power control than is possible with slow forward power control. Therefore, it is common to also provide a mechanism for fast forward power control. In fast forward power control, the mobile

10 station compares the SIR of the received signals to a reference SIR and signals the base station to either increase or decrease its transmit power. The power control commands typically comprise power control bits (PCBs), which are sent at a rate of 800 bps. A bit value of "1" signals the base station to decrease its transmit power. A bit value of "0" signals the base station to increase its transmit power. Upon receipt of a

15 power control command from the mobile station, the base station steps its transmit power up or down by a fixed amount, referred to as the step size.

Another technique used in CDMA communication systems to reduce interference is known as a soft handoff. A handoff is the act of transferring support for a mobile station from one base station to another when the mobile station moves between cells.

20 In a traditional "hard" handoff, the connection to the current base station is broken and a connection is made with the new base station to resume communication with the mobile station. This is known as a "break before make" handoff. Because all base stations in a CDMA system use the same frequency, it is possible with the connection to the new base station before terminating the connection with the current base station. This is

25 known as a "make before break" or "soft" handoff. A soft handoff requires less power, which reduces interference and increases system capacity. The set of base stations

serving a given mobile station during a soft handoff is referred to as the active set for

that mobile station.

During a soft handoff, each base station in the active set for a mobile station

transmits the same data to the mobile station. Ideally, each base station in the active set

5   transmits signals to the mobile station at the same transmit power level. System

interference is minimized when the transmit power level of all base stations in the active

set for a mobile terminal is the same, i.e. balanced. The mobile station combines the

received signals from all of the base stations in a diversity combiner. The mobile station

determines the power control commands to send by comparing the SIR of the combined

10   signals to the reference SIR. Since the power control commands are sent to all of the

base stations in the active set, the balance of the transmit power is maintained between

base stations in ideal conditions.

Unfortunately, ideal conditions are not the norm in wireless communication

systems and the power control commands transmitted by the mobile stations are often

15   subject to reception errors. When reception errors occur, the base stations may not

control transmit power correctly, and the balance of transmit power may not be

maintained between the base stations. Imbalance may occur, for example, if one of the

base stations fails to correctly receive the power control command from the mobile

station while the other base stations adjust their transmit power. This imbalance, if not

20   cancelled by additional reception errors, increases interference and results in loss of

traffic capacity in the downlink.

SUMMARY OF THE INVENTION

The present invention provides a method and apparatus to reduce forward link

25   transmit power imbalance between a plurality of base stations supporting a mobile

station in soft handoff. Periodic transmit power adjustments are made at each base

4

station responsive to power control commands received from the mobile station to provide fast forward power control. The mobile station attempts to move the transmit power of the base stations towards a target power that results in a minimum SIR at the mobile station. The step size of transmit power adjustments at each base station

5 according to the present invention varies dependent on a difference between the current transmit power of the base station and a common reference power. When a power control command from the mobile station moves the transmit power in a direction toward the common reference power (i.e., when the target power and the reference power lie in the same direction from the current transmit power of the base station), the step size is

10 increased. Conversely, when the power control command from the mobile station moves the transmit power away from the common reference power (i.e., when the target power and the reference power lie in opposite directions from the current transmit power of the base station), the step size is decreased. Thus, movements toward the common reference power are amplified and movements away from it are attenuated, which

15 effectively causes the transmit power of each base station to converge toward substantially the same value.

Because the mobile station uses its power control commands to move the base station transmit powers to a target power that results in a minimum SIR at the mobile station, the reference power may interfere with the power control when there is a

20 substantial difference between the common reference level and the target power. The base station controller of the present invention avoids the problem by dynamically adjusting the common reference power to reduce the difference between it and the target power. Such adjustments to the common reference power may be done more slowly than the rate which the base stations update their respective transmit powers

25 responsive to the power control commands from the mobile station. In one approach, the base station controller sets an initial common reference power for use by the base

stations at the beginning of soft handoff. Then, during soft handoff, the base station

controller periodically increments the common reference power up or down depending

on an indication of reception errors at the mobile station. With this approach, the

common reference power trends toward the target power.

5   By moving the common reference power toward the target power, which is not

known *a priori*, the step size of the power adjustments may be large at the outset of soft

handoff, but tends to decrease with repeated adjustments of the common reference

power. Therefore, substantial transmit power imbalances between base stations are

quickly reduced, while stability of power control by the mobile station at or near the

10   target power is maintained. Because such transmit power imbalances increase

interference within the wireless communication network, overall system capacity is

reduced. Therefore, minimizing such imbalances tends to increase system capacity.

BRIEF DESCRIPTION OF THE DRAWINGS

15   Fig. 1 is a diagram of an exemplary wireless communication network according

to the present invention.

Fig. 2 is a flow diagram illustrating exemplary logic for computing a transmit

power level at the base stations in the network of Fig. 1.

Fig. 3 is a flow diagram illustrating exemplary logic for dynamically adjusting a

20   common reference power at the base station controller of Fig. 1.

Figs. 4 and 5 illustrate the variability of transmit power adjustment step size

under different transmit power conditions.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to the drawings, Figure 1 shows a model of a wireless

communication system 10 in which the present invention may be utilized. The wireless

communication system 10 may, for example, comprise a Code Division Multiple Access

5   (CDMA) communication system. The communication system 10 comprises a plurality of

base stations 12 supporting over-the-air communications with mobile stations 50, and

one or more base station controllers 14 for allocating communication channels and other

resources used by the base stations 12. The base station controller 14 connects via a

core network 16 to external networks such as the Public Switched Telephone Network

10   (PSTN) and/or a Packet Data Network (PDN), e.g., the Internet. The core network 16

may comprise a mobile switching center (MSC) and/or packet data serving node

(PDSN), which routes traffic to and from the external networks 18.

In an exemplary embodiment, each base station 12 comprises radio resources

20 (e.g., radio transceivers for transmitting and receiving multiple radio signals) and at

15   least one processor 22, which may comprise multiple processors or processing systems,

and generally includes memory and/or other form of storage for storing operating

instructions and data. Operating under control of the BSC 14, processor 22 manages

allocation/de-allocation of radio resources and forward link transmit power for supporting

wireless communication with mobile stations 50.

20   In an exemplary embodiment, the BSC 14 comprises a base station interface 24

to communicate with base stations 12, traffic/signaling switching resources 26 to switch

traffic and signaling, a backhaul interface 28 to communicate with the core network 16,

and at least one processor 30, which may comprise multiple processors and/or

processing systems, and generally includes memory and/or other forms of storage for

25   operating instructions and data. As noted, the BSC 14 manages communication

channel allocation by controlling the base stations 12, and routes traffic and signaling

between the core network 16, and the appropriate ones of base stations 12. Further, the

BSC 14 provides support for mobility management of mobile stations 50 as they are

handed off between its associated base stations 12.

As shown in Figure 1, mobile station 50 is engaged in a soft handoff. During a

5 soft handoff, two or more base stations 12 serve the mobile station 50. The set of base

stations 12 involved in the soft handoff is referred to as the active set for the mobile

station 50. In some CDMA communication systems 100, such as IS- 95 and cdma2000

systems, all of the base stations 12 in the active set for mobile station 50 transmit the

same data on the forward link to the mobile station 50 and receive the same data from

10 the mobile station 50 on the reverse link. Mobile station 50 combines the signals

received from the base stations 12 in the active set using diversity combining

techniques, which are well known to those skilled in the art. Since combining techniques

are not material to the present invention, they are not discussed further herein.

While the mobile station 50 is in a soft handoff, forward link power control

15 maintains the quality of forward link communications while minimizing interference with

other mobile stations. The purpose of the forward link power control is to ensure that

each mobile station 50 receives signals on the forward link at a desired minimum signal

to interference ratio (SIR). In CDMA systems, system capacity is maximized if the

transmit power level of each base station 12 is controlled so that its signals arrive at the

20 mobile station 50 with the minimum required SIR.

The communication system 10 of the present invention uses a fast forward

power control algorithm that minimizes power offsets between base stations 12 during

soft handoff. The fast forward power control algorithm includes an inner power control

loop executed by the base stations 12 and an outer control loop executed by the BSC

25 14. The inner power control loop adjusts transmit power of the base stations 12

responsive to power control commands from the mobile station 50. The inner power

control loop varies the step size of transmit power adjustments based on a difference

between a current transmit power of the base station and a common reference power

P_{REF} shared by the base stations 12 involved in the soft handoff. The inner power

control loop adjusts transmit power once every PCG (1.25 msec) so that power

5   adjustments are made at the rate of 800 Hz. As will be explained in more detail below,

the inner loop power control loop adjusts step size as a function of a reference power

P_{REF}, the current transmit power P_T of the base station 12, and a convergence

coefficient β to minimize power control drift between base stations 12 during a soft

handoff.

10   The outer control loop adjusts the reference power P_{REF} used by the inner power

control loop. The outer control loop is equal to one frame or 16 PCGs so that the

reference power P_{REF} is updated at the rate of 50 Hz. The outer control loop function is

performed by the BSC 14, which signals the reference power P_{REF} and convergence

coefficient β to the base stations 12.

15   The inner power control loop implemented by the base stations 12 relies on

power control commands transmitted from the mobile station 50 to the base station 12.

During a soft handoff, the mobile station 50 compares the SIR of the combined signals

received from the base stations 12 to a reference SIR and signals the base stations 12

to either increase or decrease their transmit powers. If the measured SIR is less than

20   the reference SIR, the mobile station 50 sends an "up" signal to the base stations 12.

Conversely, if the measured SIR is greater than the reference SIR, the mobile station 50

sends a "down" signal to the base stations 12. Thus, the mobile station 50 attempts to

move the transmit powers of the base stations 12 to a target power that meets the

minimum required SIR. Power control commands are sent as power control bits (PCBs)

as is well known in the art. A bit value of "1" signals the base stations 12 to decrease their forward link transmit power. A bit value of "0" signals the base stations 12 to increase their forward link transmit power.

Upon receipt of a power control command from the mobile station 50, the base stations 12 step their transmit power up or down accordingly. In conventional CDMA communication systems, the base stations 12 step their transmit power up or down in fixed increments. In contrast, the inner power control loop of the present invention has the effect of varying the step size of the power adjustments as a function of the reference power P_{REF}, the current transmit power P_T, and the convergence coefficient β. The step size of the power adjustments at each base station 12 is dependent on a difference between the transmit power P_T of the base station 12 and the reference power P_{REF}. Thus, if the transmit powers of the base stations 12 are not in balance, the base stations 12 will adjust their respective transmit powers by different amounts. This variable power adjustment mechanism tends to reduce the transmit power imbalance between base stations 12.

The inner loop power control mechanism is described by Equation 1 below:

$$P_T(k+1) = \min\{\max\{\beta \times P_T(k) + (1 - \beta)P_{REF}(k) + \Delta_f(k+1), MinPower\}, MaxPower\}$$

Eq. (1)

The variables used in Eq. 1 are defined as follows:

$P_T(k+1)$ is the new transmit power level in dBp (dB with respect to pilot power) for the base station at time $k +1$,

$P_T(k)$ is the transmit power in dBp for the base station at time k,

10

$P_{REF}(k)$ is the reference power in dBp at time k,

$\Delta_f(k+1)$ is the fixed power adjustment in dB called for by the mobile station applied at time k+1,

β is the convergence coefficient,

5   k is the current time in units of 1.25 msec PCGs,

MinPower is the minimum transmit power in dB allowed, and

MaxPower is the maximum transmit power in dB allowed.

As shown in Eq. 1, each base station 12 computes a provisional transmit power

10   defined by the term $\beta \times P_T(k) + (1-\beta)P_{REF}(k) + \Delta_f(k+1)$, denoted herein as P_{PROV},

and compares it to *MinPower* and *MaxPower*. If the limits *MinPower* or *MaxPower*

are not exceeded, the base station 12 sets the new transmit power $P_T(k+1)$ equal to

P_{PROV}. Otherwise, it sets the new transmit power to *MinPower* (if the lower limit is

exceeded) or to *MaxPower* if the upper limit is exceeded.

15   Figure 2 is a flow diagram illustrating an power control procedure 100 according

to the present invention implemented at each base station 12. The flow diagram shown

in Fig. 2 corresponds to the inner power control loop performed by the base stations 12.

The power control procedure 100 is triggered when a power control command is

received at the base station 12 (block 102). It should be noted that there is a time delay

20   τ between the transmission of a power control command and the time that the power

control command is decoded. Therefore, the base station 12 computes its transmit

power at time $k+1$ based on the power control bit sent by the mobile station 50 at time

$k+1-\tau$. That is, the value of $\Delta_f(k+1)$ depends on the power control bits sent at time

$k+1-\tau$. If no power control command is received, for example, because the receiver is

out of lock, $\Delta_f(k+1)$ is assumed to be 0. The computation of $\Delta_f(k+1)$ is shown in

Equation 2 below:

$$\Delta_f(k+1) = \begin{cases} \Delta^{up} & if & PCB(k+1-\tau) = Up \\ 0 & if & OutofLock \\ -\Delta^{down} & if & PCB(k+1-\tau) = Up \end{cases}, \qquad \text{Eq. (2)}$$

where Δ^{up} and Δ^{down} are positive numbers in dB.

5   Upon receipt of the power control command from the mobile station 50, the base

station 12 computes a provisional transmit power P_{PROV} (block 104). The base station

12 compares the provisional transmit power P_{PROV} to *MinPower* at block 106 and to

MaxPower at block 110. If the provisional transmit power P_{PROV} is less than

MinPower, the new transmit power $P_T(k+1)$ is set equal to *MinPower* (block 108). If

10   the provisional transmit power P_{PROV} is greater than *MaxPower*, the base station 12

sets the new transmit power $P_T(k+1)$ equal to *MaxPower* (block 112). If the

provisional transmit power P_{PROV} is greater than *MinPower* and less than *MaxPower*,

the base station 12 sets the new transmit power $P_T(k+1)$ equal to the provisional

transmit power P_{PROV}.

15   The computation of the provisional transmit power P_{PROV} in step 104 is worthy of

some explanation. The term $\beta \times P_T(k) + (1 - \beta)P_{REF}(k)$ in Eq. (1) is a weighted sum of

the current transmit power level $P_T(k)$ and the current reference power $P_{REF}(k)$ before

the power adjustment. The base station 12 computes this weighted sum and adds it to a

fixed power adjustment term $\Delta_f(k+1)$ to obtain the provisional transmit power P_{PROV}.

20   The term $\beta \times P_T(k) + (1 - \beta)P_{REF}(k) + \Delta_f(k+1)$ in Eq. (1) is mathematically equivalent

to Eq. 3 below:

$$P_T(k) + (1 - \beta)(P_{REF}(k) - P_T) + \Delta_f(k+1) \qquad \text{Eq. (3)}$$

The term $(1 - \beta)(P_{REF}(k) - P_T)$ in Eq. 3 may be considered a variable power adjustment term applied at time $k+1$, which is denoted herein as $\Delta_v(k+1)$. Therefore Eq. 3 may be rewritten as:

5

$$P_T(k) + \Delta_v(k+1) + \Delta_f(k+1) \qquad \text{Eq. (4)}$$

In Eq. (4) the sum $\Delta_v(k+1) + \Delta_f(k+1)$ represents the amount of the total power adjustment, which comprises a fixed component $\Delta_f(k+1)$ and a variable component $\Delta_v(k+1)$. The variable component $\Delta_v(k+1)$ is dependent on the difference between the current reference power $P_{REF}(k)$ and the current transmit power $P_T(k)$ of the base

10 station 12 before the power adjustment. The fixed component $\Delta_f(k+1)$ represents either a positive step Δ^{up} or negative step $-\Delta^{down}$ of a fixed magnitude that depends on the power control command from the mobile station 50. If the mobile station 50 signals the base station 12 to increase power, $\Delta_f(k+1)$ is a fixed upward adjustment value Δ^{up}. If the mobile station 50 signals the base station 12 to reduce power, $\Delta_f(k+1)$ is a

15 fixed downward adjustment value $-\Delta^{down}$. The magnitude of the fixed upward adjustment value Δ^{up} and the fixed downward adjustment value $-\Delta^{down}$ may be the same or may be different.

The net effect of the power adjustment calculation in step 104 is to vary the step size of the power adjustment made by the base station 12 dependent on the difference

20 between the current transmit power level $P_T(k)$ at the base station 12 and the current reference power $P_{REF}(k)$. When the current transmit power level $P_T(k)$ and the current reference power $P_{REF}(k)$ are equal, the amount of the power adjustment is equal to the

fixed component $\Delta_f(k+1)$. When the transmit power $P_T(k)$ of a base station 12 drifts

away from the reference power $P_{REF}(k)$, the inner power control loop tends to resist

further movement away from the reference power $P_{REF}(k)$ by reducing the step size of

the power adjustment and to accelerate movement towards the reference power

5    $P_{REF}(k)$ by increasing step size of the power algorithm. This behavior of the inner loop

power control loop is illustrated in Figures 4 and 5.

Figure 4 shows the transmit power level of two base stations 12, referred to in

this example as BS1 and BS2, before and after a power adjustment. BS1 is represented

by circles in Figure 4, and BS2 is represented by triangles. The current transmit powers

10   of the respective base stations 12 are denominated by the notation $P_T^i(k)$, where i is an

index denoting the number of the base station 12. As shown in Figure 4, the current

transmit power for both base stations 12 is greater than $P_{REF}(k)$. In this example, the

mobile station 50 signals the base stations 12 to increase their respective transmit

powers. In conventional CDMA communication systems, power adjustments are made

15   in fixed step sizes. However, the implicit variable power adjustment term $\Delta_v(k+1)$ in

the inner power control loop of the present invention causes the step sizes to vary. In

the example of Figure 4, the target power sought by the mobile station 50 and the

reference power $P_{REF}(k)$ lie in opposite directions from the current transmit powers of

the base stations 12. In this case, the base stations 12 are adjusting their respective

20   transmit powers so as to move away from $P_{REF}(k)$. When the power adjustment is in a

direction away from $P_{REF}(k)$, the variable power adjustment term $\Delta_v(k+1)$ causes the

step size to be reduced by an amount proportional to the difference between the current

reference power $P_{REF}(k)$ and the current transmit power $P_T(k)$ of the base station 12.

Thus, while both base stations 12 will increase the transmit power on the traffic channel,

BS2 will increase its transmit power by a lesser amount than BS1. In the example

shown in Fig. 2, BS1 increases its transmit power by an amount equal to Δ^1_{ADJ}, while

BS2 increases its transmit power by an amount equal to Δ^2_{ADJ}, where Δ^2_{ADJ} is less than

Δ^1_{ADJ}. In both cases, the magnitude of the power adjustment Δ^i_{ADJ} is less than the fixed

5   power adjustment term $\Delta_f(k+1)$. Thus, the variable power adjustment term

$\Delta^i_v(k+1)$ reduces the step size of the total power adjustment.

Figure 5 illustrates the effect of the variable power adjustment term $\Delta_v(k+1)$

when the power adjustment is in the direction of $P_{REF}(k)$. As shown in Figure 5, the

current transmit power $P_T(k)$ of the base stations 12 before the power adjustment is

10   greater than $P_{REF}(k)$. The target power sought by the mobile station 50 is less than the

reference power $P_{REF}(k)$ so the mobile station 50 signals the base stations 12 to reduce

their transmit powers. In this case, both base stations 12 adjust their respective transmit

powers so as to move towards the reference power $P_{REF}(k)$. The variable power

adjustment term $\Delta_v(k+1)$ amplifies the downward adjustment by an additional amount

15   proportional to the difference between the current transmit powers $P^i_T(k)$ of the

respective base stations 12 and the reference power $P_{REF}(k)$. In the example shown in

Fig. 5, BS1 decreases its transmit power by an amount equal to Δ^1_{ADJ}, while BS2

increases its transmit power by an amount equal to Δ^2_{ADJ}, where Δ^2_{ADJ} is greater than

Δ^1_{ADJ}. Since the transmit power $P^2_T(k)$ for BS2 is greater than the transmit power

20     $P^1_T(k)$ for BS1, BS2 will make a larger power adjustment than will BS1. In both cases,

the magnitude of the power adjustment Δ^i_{ADJ} is greater than the magnitude of the fixed

power adjustment term $\Delta_f(k+1)$. Thus, the variable power adjustment term

$\Delta^i_v(k+1)$ amplifies the step size of the total power adjustment when moving in the

direction of $P_{REF}(k)$.

As shown in Figures 4 and 5, the effect of the variable power adjustment term

5 $\Delta_v(k+1)$ is to vary the step size of power adjustments dependent on a difference

between the reference power $P_{REF}(k)$ and the current transmit power $P_T(k)$ of the base

station 12. When the transmit power $P_T(k)$ of all base stations 12 in soft handoff is

balanced, the amount of the power adjustments will be the same for all base stations 12.

However, when the transmit power levels are imbalanced, as shown in Figures 4 and 5,

10 the variable power adjustment term $\Delta_v(k+1)$ applied independently at each base

station 12 reduces the amount of the imbalance by varying the step sizes of the power

adjustments for the base stations 12 by different amounts. The net effect of the power

adjustments is to reduce the transmit power imbalance between base stations 12 from

$\operatorname{Im} b(k)$ to $\operatorname{Im} b(k+1)$. The sensitivity of the power adjustments to differences between

15 reference power P_{REF} and transmit power P_T is determined by the convergence

coefficient β, which is always a value between 0 and 1. When β is small, the transmit

powers P_T of the base stations 12 will converge more rapidly towards the reference

power P_{REF} than when β is large.

If the reference power P_{REF} is arbitrarily chosen, the reference power P_{REF} may

20 differ substantially from the target power sought by the mobile station 50 that is needed

to maintain the desired SIR. In this case, the inner power control loop becomes less

responsive to power control commands from the mobile station 50 since it has to

compensate for differences between the current transmit power $P_T(k)$ and the reference

power $P_{REF}(k)$. This difference can have a negative impact on performance of the inner power control loop. This negative impact is illustrated in Fig. 4 where the reference power $P_{REF}(k)$ impedes adjustment towards the desired target power. To avoid the negative impact, a large value may be chosen for the convergence coefficient β, but

5   this reduces the rate of convergence between the two base stations 12 resulting in a reduction of system capacity. Therefore, it is desirable to that the reference power $P_{REF}(k)$ be as close as possible to the target power. This problem is addressed in the present invention by the outer control loop.

The outer control loop according to the present invention periodically adjusts the

10   reference power P_{REF} used by the inner power control loop to urge it closer to the target power sought by the mobile station 50 that results in the minimum SIR. The outer control loop is based on an error report message received form the mobile station 50. The power measurement report message (PMRM) incorporated in the IS-95 and IS-2000 standards published by the Telecommunications Industry Association (TIA) and

15   Electronics Industry Association (EIA) may be used in the present invention to provide the error reports. In one embodiment of the invention, the mobile station 50 in a soft handoff keeps a count of the number of frame erasures or error frames. When the count of the frame erasures reaches a predetermined threshold, e.g., a count of two, the mobile station 50 sends a PMRM to the base stations 12 and resets its counter. The

20   PMRM may contain the number of frames received since the last PMRM and the number of frame erasures, as well as other information.

Those skilled in the art will appreciate that other criteria may be used to trigger a PMRM from the mobile station 50. For example, the mobile station 50 could be programmed to report the FER at predetermined intervals, or when the FER reaches a

predetermined threshold. These and other equivalent variations of the PMRM are within the scope of the present invention.

The BSC 14 adjusts the reference power P_{REF} based on the PMRMs from the mobile station 50, once every 20 msec frame. As described in more detail below,

5 adjustment of the reference power based on the PMRM includes adjustment when no PMRM is received in a designated time period. The outer control loop is described by Equation 5 below:

$$P_{REF}(n+1) = \min\{\max\{P_{REF}(n) + \delta(n+1), Min\,\mathrm{Re}\,fPower\}, Max\,\mathrm{Re}\,fPower\}$$

Eq. (5)

10 The variables in Eq. (5) are defined as follows:

$P_{REF}(n+1)$ is new reference power in dBp,

MinRefPower is the minimum reference power in dBp,

MaxRefPower is the maximum reference power in dBp,

$\delta(n+1)$ is the adjustment term in dB applied at time $k+1$, and

15 n is the current time in frames.

As shown in Eq. (5), BSC 14 computes the new reference power $P_{REF}(n+1)$ each frame by increasing or decreasing the current reference power $P_{REF}(n)$ and comparing the result to $Min\,\mathrm{Re}\,fPower$ and $Max\,\mathrm{Re}\,fPower$. If the limits $Min\,\mathrm{Re}\,fPower$ and $Max\,\mathrm{Re}\,fPower$ are not exceeded, the BSC 14 sets the new

20 reference power $P_{REF}(n+1)$ equal to $P_{REF}(n) + \delta(n+1)$. Otherwise, it sets the new reference power $P_{REF}(n+1)$ to $Min\,\mathrm{Re}\,fPower$ (if the lower limit is exceeded) or to $Max\,\mathrm{Re}\,fPower$ (if the upper limit is exceeded).

Figure 3 is a flow diagram illustrating the control procedure 200 implemented in the BSC 14. The procedure begins when the mobile station 50 establishes a call (block

202). Alternatively, the procedure 200 could be started when the mobile station 50

begins a soft handoff. When the call begins, the BSC 14 initializes the reference power

P_{REF} to a default value and signals the reference power P_{REF} to all base stations 12

communicating with the mobile station 50. After the reference power P_{REF} is initialized,

5 the BSC 14 updates the reference power P_{REF} once every frame. At block 206, the BSC

14 waits until the end of frame (EOF) is reached. At the end of each frame, the BSC 14

determines whether a power measurement report message (PMRM) was received from

the mobile station 50 during the preceding frame (block 208). If the BSC 14 did not

receive a PMRM from the mobile station 50, the BSC 14 decreases the current

10 reference power $P_{REF}(n)$ (block 210). On the other hand, if the BSC 14 receives a

PMRM (block 208), the BSC 14 increases the reference power $P_{REF}(n)$ and signals the

updated reference power $P_{REF}(n+1)$ to the base stations 12 (block 212). When the

BSC 14 detects that the mobile station 50 is in a soft handoff (block 214), the BSC 14

signals the current reference power $P_{REF}(n)$ to the base stations 12 involved in the soft

15 handoff (block 216). When the BSC 14 detects that the call has ended (block 218), the

procedure terminates (block (220). As long as the procedure 200 is running, the

reference power is updated once every 20 msec frame.

The computation of the updated reference power in blocks 210 and 212 is shown

in Eq. 5. As shown in Eq. 5, the updated reference power $P_{REF}(n+1)$ is equal to the old

20 reference power $P_{REF}(n)$ plus a fixed increment $\delta(n)$. The fixed increment $\delta(n)$ is a

fixed positive adjustment δ^{up} when a PMRM is received, and a fixed negative

adjustment $-\delta^{down}$ when no PMRM is received. This calculation is shown in Eq. (6)

below:

$$\delta(n) = \begin{cases} \delta^{up} & if \quad PMRM = TRUE \\ -\delta^{down} & if \quad PMRM = FALSE \end{cases} \qquad \text{Eq. (6)}$$

where δ^{up} and δ^{down} are fixed positive values.

In a preferred embodiment of the invention, the downward step size δ^{down} for a negative adjustment of the reference power P_{REF} is smaller than the upward step size

5   δ^{up} for positive adjustments of the reference power P_{REF}. The downward step size

δ^{down} may be a small fraction of the upward step size δ^{up}. Thus, when a PMRM is received, the base station 12 makes a relatively large upward adjustment in the reference power P_{REF} and makes smaller downward adjustments in frames when no PMRMs are received.

10   Those skilled in the art will appreciate that additional methods of computing the adjustments to the reference power could be utilized. For example, the BSC 14 could, in some embodiments, extract a FER from PMRMs sent once every frame (or some other designated period) and adjust the reference power based on the reported FER. This approach would, however, increase the signaling required compared to procedure

15   shown in Eq. (6).

The outer control loop, in effect, predicts a reference power P_{REF} that is close to the target power that results in the minimum SIR. As a result, the present invention may use a more aggressive (lower) convergence coefficient β which makes the inner power control loop more sensitive to differences between the current transmit power $P_T(k)$ and

20   the reference power $P_{REF}.(k)$. Consequently, the present invention will more quickly restore transmit power balance between base stations 12 in a soft handoff when an imbalance occurs. Another benefit of the present invention is that the dynamic reference power P_{REF} can be used to control the base station transmit power when the base

station 12 does not receive the power control commands from the mobile station 50. The dynamic reference power may also be used to initialize forward transmit power for base stations 12 at the start of the soft handoff.

5   The present invention may, of course, be carried out in other specific ways than those herein set forth without departing from the spirit and essential characteristics of the invention. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive, and all changes coming within the meaning and equivalency range of the appended claims are intended to be embraced therein.